WL-TR-93-4047

X-RAY COMPUTED TOMOGRAPHY FOR FAILURE ANALYSIS INVESTIGATIONS

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Failure analysis is an important engineering evaluation in any product development cycle; essential to product reliability and evolution. The volumetric feature detection and three-dimensional positioning capability of X-ray computed tomography are valuable and cost saving assets to a failure analysis laboratory. Savings are realized in reduced risk, determination of proper direction for irreversible failure analysis activities and schedule improvement. Savings are realized in reduced risk, determining proper direction for irreversible failure analysis activities and schedule improvement. Failure analysis laboratories of sufficient size can justify the cost saving benefits of using CT for equipment procurement.

Case studies of failure analyses have been demonstrated to the Air Force and industry showing the ability of CT to significantly benefit such studies. In some cases, CT can directly resolve the problem, and in other cases, provides key supplemental information for guiding further investigations and reducing the risk of incorrect or incomplete analysis. Examples have included mechanical and electrical system assembly, system internal measurements and fitups, and material damage evaluation. CT also can be applied to systems to observe the internal positions as a function of test conditions. High resolution (>4 lp/mm) CT with combined radioscopy (real-time radiography) capability is advocated for failure analysis facilities.

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DISCLAIMER

SUMMARY

Failure analysis is an important engineering evaluation in any product development cycle. Proper failure studies are essential to product reliability and evolution. The volumetric feature detection and three dimensional positioning capability of X-ray computed tomography is a valuable and cost saving asset to a failure analysis laboratory. Savings are realized in reduced risk, determination of proper direction for irreversible failure analysis activities and schedule improvement. Under a demonstration task assignment of the Advanced Development of X-ray Computed Tomography Application program, computed tomography (CT) has been evaluated for its benefits to assist failure analysis investigations.

CT provides three-dimensional spatial distribution of material that can be used to assess internal configurations and material conditions nondestructively. Case studies of failure analyses have been demonstrated to the Air Force and industry showing the ability of CT to significantly benefit such studies. In some cases, CT directly resolves the problem, and in other cases, CT provides key supplemental information for guiding further investigations and reducing the risk of incorrect or incomplete analysis. Examples have included mechanical and electrical system assembly, system internal measurements and fitups, and material damage evaluation. CT also can be applied to systems to observe the internal positions (mechanical and material) as a function of test conditions.

CT is an important tool for the failure analyst that needs to be considered whenever an investigation is undertaken. The role of CT will depend on the "problem at hand" in each particular cases and the availability of appropriate CT capability. For electromechanical systems, CT with 400 kV or higher energy and resolutions to better than 0.25 mm are desired. For electrical systems, high resolution CT of the order of 0.1 mm is desired. A combination high resolution (>4 lp/mm) and real-time radiography capability system is advocated for electronic component failure analysis laboratories. For composite materials development studies, higher resolution (>8 lp/mm) is desired. However, CT systems with only medium resolution (1 lp/mm) have been used effectively in a number of failure analysis investigations on electromechanical systems, electronic components and composite structures. While a few case studies can demonstrate a simple, direct cost saving by using CT as opposed to other methods (including disassembly and destructive sectioning), the technique provides many benefits that are much more difficult to quantify in terms of dollars. CT frequently helps to guide the direction of further, irreversible, evaluations reducing overall program cost through schedule savings and reduction of risk.

1.0 INTRODUCTION

The goal of the Advanced Development of X-Ray Computed Tomography Applications demonstration (CTAD) program is to evaluate inspection applications for which X-ray computed tomography (CT) can provide a cost-effective means to evaluate aircraft/aerospace components. The program is "task assigned" so that specific CT applications or application areas can be addressed in separate projects. Three categories of task assignments are employed in the program: 1) preliminary tests where a variety of parts and components in an application area are evaluated for their suitability to CT examinations, 2) final tests, where one or a few components are selected for detailed testing of CT capability to detect and quantify defects, and 3) demonstrations, where the economic viability of CT to the inspection problem are analyzed and the results presented to government and industry. This interim report is the result of a demonstration task assignment study on failure analysis. Additional task assignment reports issued by the CTAD program are listed in References 1 through 14.

1.1 Computed Tomography

X-ray computed tomography (CT) is a powerful nondestructive evaluation technique that was conceived in the early 1960's and has been developing rapidly ever since. CT uses measurements of X-ray transmission from many angles about a component to compute the relative X-ray linear attenuation coefficient of small volume elements and presents them as a cross-sectional image map. The clear images of an interior plane of an object are achieved without the confusion of superposition of features often found with conventional film radiography. CT can provide quantitative information about the density/constituents and dimensions of the features imaged.

Although CT has been predominantly applied to medical diagnosis, industrial applications have been growing over the past decade. Medical systems are designed for high throughput and low dosages specifically for humans and human sized objects. These systems can be applied to industrial objects that have low atomic number and are less than one-half meter in diameter. Industrial CT systems do not have dosage and size constraints. They are built in a wide range of sizes suitable for the inspection of small components (such as test coupons or jet engine turbine blades) using low to mid-energy (hundreds of kV) X-ray sources to the inspection of large ICBM missiles requiring high (MV level) X-ray energies. The appropriate industrial CT system required for any particular component inspection depends on the size of the component and sensitivity required to evaluate the details of interest in the component.

1.2 Scope and Objective

This task assignment, designated "Task 13 - Failure Analysis Investigation," was directed at reviewing earlier applications of CT to failure analysis under previous task assignments to develop demonstration material. The effort included finding additional examples of benefits to failure analysis investigations and generalizing the lessons learned. Development of an applications logic diagram and refinement of cost/benefits analysis were emphasized in the effort.

The overall goal of this task assignment was to present to the Air Force and industry the technical feasibility and economic viability of using CT as part of failure analysis efforts. Specific objectives included the usefulness in a variety of failure analysis studies, such as assembly verification, dimensional tolerances, foreign object detection, defects, and material variations. Presentation materials included posters and viewfoils developed for an industry demonstration at the Air Force Computed Tomography Applications Workshop held May 5-7, 1992 in Salt Lake City, Utah. Materials were also prepared for an "Interactive Presentation for Applied Computed Tomography" (IMPACT) software multimedia package designed to operate on Macintosh workstations. The package can be obtained from the Air Force Wright Laboratory Materials Directorate, NDE Branch.

2.0 BACKGROUND

The CTAD program identified failure analysis activities as an important appl`ation area in several preliminary and final task assignments [1,6,11,12]. Task assignment 11, "`ure Analysis" [12], specifically included evaluation of CT on selected parts ex`acted from typical work loads of Boeing's Equipment Quality Analysis (EQA), Parts Engineering Failure Analysis, and Materials Development laboratories. Effectiveness of CT in failure analysis was assessed and preliminary cost/benefit trades were develope`. This task assignment (Task 13, "Failure Analysis Investigations") extends this initial e`fort through review of past results and lessons learned, development of criteria for use of CT in failure analysis, and the evaluation of benefits. The objective is to provide potential users a systematic method for determining the efficacy of CT in their applications. In this process, additional examples of parts and materials requiring failure analysis were identified and tested at appropriate facilities. In addition, educational materials on the application of CT were developed and presented at the Air Force Computed Tomography Applications Workshop held May 5-7, 1992 in Salt Lake City, Utah.

2.1 Review of Earlier Task Results

Failure analysis is broadly defined to include both determination of the mode of failure of malfunctioning parts, materials and assemblies and evaluation of the performance of developmental items against their design specifications. The primary sources of test items were The Boeing Company engineering and failure analysis investigation groups. Failure analysis at Boeing tends to break down into three categories based on the laboratories to which they are assigned. These are the Equipment Quality Analysis (EQA) laboratory which is responsible for mechanical and electromechanical assemblies, the Parts Engineering and Failure Analysis (PEFA) laboratory which is primarily responsible for electrical and electronic devices, and various materials and process development laboratories responsible for engineering and evaluation of aerospace materials and assemblies.

Table 2.1-1 lists a number of items which were identified in the CTAD program as being aided by CT in their failure analysis. The table identifies the class into which they fall, indicates the nature of the evaluation required, and summarizes the utility of CT in the analysis. The CTAD report in which the analysis is given is also identified.

It is interesting to note that only 57% of the entries in the table involve failed assemblies. The remainder are for establishing the internal condition of potentially viable parts, or assessing the physical status of developmental items. In every case, the essential contribution of CT is that it provides visualization of internal volumes, often in very complex assemblies, that cannot be adequately evaluated by disassembly or destructive methods.

The two autobrake modules exhibited failure modes that would not be directly identified upon disassembly because removal of the individual parts would erase the evidence of improper spring placement in the first case and of failure of the valve spool to seat in the second case. Standard radiographs do not, in general, reveal these defects because of intervening structure that hampers image interpretation.

The solenoid valve represents a case illustrating two points. The first is that the CT system capability must be matched to the inspection requirement; there are no universal scanners. In this case, the use of medium resolution was inappropriate for assessing the seating of the ball seal to the tolerance required to be effective in an hydraulic system. The less obvious point is that the medium resolution (1 to 2 lp/mm) CT scan may still be useful in this application. A variety of cases have been encountered where the scan suggests that an assumed failure cause is not probable so that attention is directed to more likely possibilities. In another application, the resolution was insufficient for detection of suspected fine particulate contamination of a

Table 2.1-1 CT Failure Analysis Test Summary

ITEM DESCRIPTION (AIR FORCE CTAD REPORT)	CLASS	REQUIRED EVALUATION	UTILITY OF CT
Autobrake Module, Type 1 (WL-TR-92-4017)	Electro-mechanical	Out of specification hydraulic pressure control	Internal visualization of part identified misaligned pressure control spring which would have been dislodged during disassembly
Autobrake Module, Type 2 (WL-TR-92-4017)	Electro-mechanical	Incomplete shut-off of anti-skid valve	Insitu visualization demonstrated that shutoff spool valve was not seating. It is likely this would have been obscured by disassembly
Solenoid Valve (WL-TR-92-4017)	Electro-mechanical	Evaluation of valve, damaged in a fire	Medium resolution CT could not verify valve sealing integrity to the necessary level of confidence. Requirement for high resolution CT indicated
Instrumentation Wafer Antenna (WL-TR-92-4017)	Electrical-Electronic	Antenna performance at margin of design envelope	Isolated performance deficiency to antenna element dimensional tolerance. Eliminated more serious potential problems. Part cleared for installation
Drag Brace with Experimental Bearing (WL-TR-92-4017)	Mechanical	Nondestructive evaluation of the performance of an experimental bearing assembly	Established that bearing assembly was deforming beyond design goal. Led to redesign. Information potentially obscured if part sectioned
Aircraft Fuel Line (WL-TR-92-4017)	Mechanical	Evidence of engine fuel starvation	CT of fuel line section under ambient, vacuum, and pressurization established that suspect section could not deform to restrict fuel flow

Table 2.1-1 CT Failure Analysis Test Summary (Cont.)

ITEM DESCRIPTION (AIR FORCE CTAD REPORT)	CLASS	REQUIRED EVALUATION	UTILITY OF CT
Power Transformer (WRDC-TR-89-4112)	Electrical-Electronic	Evaluate low inductance	CT showed a shifted core which might not have been properly identified if sectioning had been used
Compressed Ferrite Core Transformer (WRDC-TR-90-4091)	Electrical-Electronic	Low measured inductance	Very high resolution CT identified in-depth cracking of core. High resolution CT also found lamination shift.
Relay (WRDC-TR-89-4112 WRDC-TR-90-4091)	Electrical-Electronic	Apparent welded contact	High resolution CT scanner could not prove welding unambiguously but, image supported conclusion
RF Relay (WRDC-TR-89-4112)	Electrical-Electronic	Electrical discontinuity; multiple possibilities	CT showed that a contact was missing. Eliminated mechanical malfunction as cause.
Honeycomb Panel (WL-TR-92-4017)	Materials	Evaluate effectiveness of CT for identification of damage and isolation of cause	Established damage to honeycomb cell walls and face-sheets associated with probable anisotropic loading of honeycomb. Tedious destructive sectioning avoided; damage evidence retained
Composite Damage - Impact Test Specimen (WL-TR-92-4017)	Materials	Evaluate internal damage resulting from impact testing	Demonstrates mapping of delamination without necessity of sectioning lamina by lamina
Composite Damage - Stress Cracking at Hole for Fastener (WL-TR-92-4017)	Materials	Evaluate internal damage at through hole for fastener in graphite epoxy	Numerical processing of CT data file clearly defined cracking and delamination pattern throughout volume without sectioning

defective valve seat, but the detailed CT image was valuable in the required disassembly of the valve because it afforded a clear view of the internal relationship of parts that was not easily appreciated from the standard break-out drawing supplied by the manufacturer.

The instrumentation wafer antenna represents a case of a part that had not failed but was operating near the limits of its allowable envelope. The issue was whether a potential failure was indicated. CT sectioning, in this case, showed that the internal antenna element was physically adjusted so as to cause the deviation in the tolerance band. No defective elements were found in the assembly and the device could be placed into service with confidence. Although conventional radiography was a potential candidate for internal inspection of the antenna, it was judged that CT was the most effective means of providing the clear view of the assembly needed to assure its integrity and establish the dimensions of the radiating element. All other applicable inspection procedures would have resulted in destruction of the unit, which was counter to the intention of the user. This type of inspection is often a highly leveraged application of CT.

The drag brace, fuel line and raceway cable represent assemblies that benefit considerably from CT examination. In each case, the essential required information involved volumetric features that could not be assessed without destructive procedures. In the case of the fuel line, a reinforcing sheath surrounded and supported a flexible tube. The performance of the system could only be determined in an intact condition; destructive evaluation was not an option. CT also aided the analysis by allowing the evaluation of the fuel line under several pressure conditions. Sectioning of the bearing in the drag brace is the traditional method of examination. However, this destroys the part and may introduce additional damage not associated with stresses applied in use. It is also not applicable to inspection of the bearing under load. CT can accomplish the latter, and permits additional testing of the bearing if it is found that performance is within design limits. Failure of the raceway cable resulted from displacement of wire pairs towards the apex of the raceway channel. This was not directly observable owing to the potting material. Sectioning could detect the problem, but it was not known, a priori, where to look. CT afforded a simple, rapid means of examining large sections of the cable. In addition, it identified a second, potential problem area in the transition to the terminating connector.

In the power transformer case, CT identified offsets in some of the core lamina that could either contribute to, or be the cause of low inductance (core cracking was also identified in one of the transformers). This represents an example of CT analysis that not only eliminated the need for transformer sectioning, but, most importantly, identified a defect (core shifting) that could easily have been introduced during sectioning, leaving the cause of transformer low inductance an open question.

Damage in the small transformer and the two relays was fairly subtle. These are instances where having the capability for both radioscopy (real-time radiography) and CT greatly enhances the capability for correct failure diagnosis. Radioscopy makes it possible to manipulate the part while viewing radiographic images and, in the case of the relays, to operate them. This can often help the analyst to detect anomalies which would be less obvious in static views and which could require numerous CT slices to be taken to focus on a specific problem area. Then, with the number of possible areas of likely abnormality reduced, CT provides capability for sectional analysis of suspect features. It also provides a means of making dimensional measurements that may be required to confirm a postulated failure mode. Radioscopy and CT are available as complementary capabilities of a single X-ray analysis system.

CT inspection of the three organic composite specimens provided an alternative to the difficult and time consuming, layer-by-layer sectioning required for failure analysis in this class of materials. In addition, use of numerical processing techniques on the digital data file, which is the standard output of the CT measurement and data processing system, was shown to be capable of producing a volumetric map of the internal disruption of the samples. Such data should, in principle, be

valuable for understanding the internal stress distribution and material response in appropriate composite samples.

2.2 Cost Benefit Analysis

As may be apparent from the preceding subsection, there are significant technical benefits to be realized through the use of CT. In a number of individual cases, CT provides the only means of developing information necessary for a clear understanding of the performance of materials and assemblies of interest. However, since CT scanners can be very expensive in comparison to other applicable technologies, it is important to develop a systematic method for evaluating costs and benefits in any potential application. The work performed focussed on the types of problems common to a large aircraft and aerospace manufacturer. The work loads of the Boeing EQA and PEFA laboratories were evaluated with respect to the probable applicability of CT. The EQA laboratory typically handles mechanical and electromechanical systems, while the PEFA laboratory generally handles electrical and electromechanical components. The results were ranked into five categories with letter designations: (O) CT provides unique or Only capability; (B) CT is Best choice of several with respect to time and/or information; (D) CT is competitive with or Duplicates other technique in expenditure of time; (C) CT is applicable but too Costly, and CT is not applicable (NA). Table 2.2-1 summarizes results for the two laboratories, respectively. Based on the analysis of the 1990 work loads, it was concluded that approximately 36% of the PEFA laboratory load and 9% of EQA laboratory load could benefit from the application of CT (assuming the availability of appropriate scanners). Since the time of this analysis, the workload for the PEFA laboratory has increased in items that would benefit from CT examination, such that in 1993 over 50% of the workload is estimated to benefit from CT.

Table 2.2-1 PEFA and EQA Laboratories Applicability of CT

	Total	(O)nly	(B)est	(D)uplicate	(C)ostly	NA
1990 PEFA	205	2	40	31	5	127
Percent of Tests		1	20	15	2	62
1990 EQA	215	1	5	13	7	190
Percent of Tests		1	2	6	3	88

Folding in information about the time savings associated with CT inspection and the average hourly rates involved, it is possible to derive figures for the cost impact of using CT and compare these with capital investment and maintenance expenses for required facilities to estimate cost benefits. These figures, however, leave out the value of parts saved for future use, the advantages of rapid resolution of engineering issues, the intangible value of increased confidence in assemblies in use, and the considerable value of improved customer and supplier relations derived from clear identification and timely solutions to hardware problems.

Example estimations of specific cost savings for some of the assemblies identified in Table 2.1-1 were presented in earlier reports [1,6,12]. In reference 12, "X-ray Computed Tomography for Failure Analysis," an analysis was developed for the use of CT in the PEFA and EQA laboratories at Boeing to provide some perspective on the economic value of CT in an environment where yearly failure analysis investment is large and critical to the success of the product lines. The report [12] provided estimation curves for making buy/no-buy decisions for CT purchase based on

the operating budgets of failure analysis laboratories, and it presented graphics identifying the probable best CT system choices for typical laboratory applications.

An effort made during this task to categorize the benefits of CT and demonstrate and, systematize the failure analysis process and the justification of equipment acquisition is discussed in Section 4, below.

2.3 Applications Logic

The CTAD effort has helped to clarify the useful role of CT in the failure analysis laboratory. Clearly, not all failure analyses benefit from CT and, in many cases, the technique is not applicable. Similarly, the large variety of materials and assemblies to be examined require a variety of CT systems ranging from compact, low and medium energy, high resolution systems to large scale, high energy systems capable of handling large, heavy parts. In the course of conducting the analyses previously presented, a methodology was evolved to evaluate the use of CT in parts analysis.

The first step in applying CT is deciding whether it serves a useful purpose in a given parts analysis task. This involves a decision as to the technical merits of CT for revealing essential information about a given material or assembly, as well as the benefit of the information relative to its cost. Figure 2.3-1 presents a logic flow diagram intended to systematize the process of evaluating CT applications technically. The tree ultimately leads to a branch that involves an evaluation of the cost/benefit ratio for the particular object under consideration. In many cases, the resolution of this question will be clear to the laboratory considering CT. Information presented in Section 4 is intended to help with this decision point as well. Experience has emphasized that the essential contribution of CT to failure analysis is its ability to clearly represent volumetric characteristics of objects with high fidelity and dimensional accuracy. Therefore, the first branch of the decision tree asks whether the required information involves volumetric features. If not, the logic tree is exited. A basic decision follows as to whether an X-ray technique is superior to other NDE methods such as ultrasonic testing, for example. Thereafter, well established techniques such as disassembly (nondestructive or destructive) and standard radiography are tested. This leads to an evaluation of CT as a diagnostic. It may not be applicable because object properties are not compatible with the operating characteristics of any type of CT scanner. Note that the tree recognizes that, while CT may not provide all required information, it may still provide support for other diagnostics that will justify its application. The tree does not address the availability of a particular type of scanner to the failure analyst.

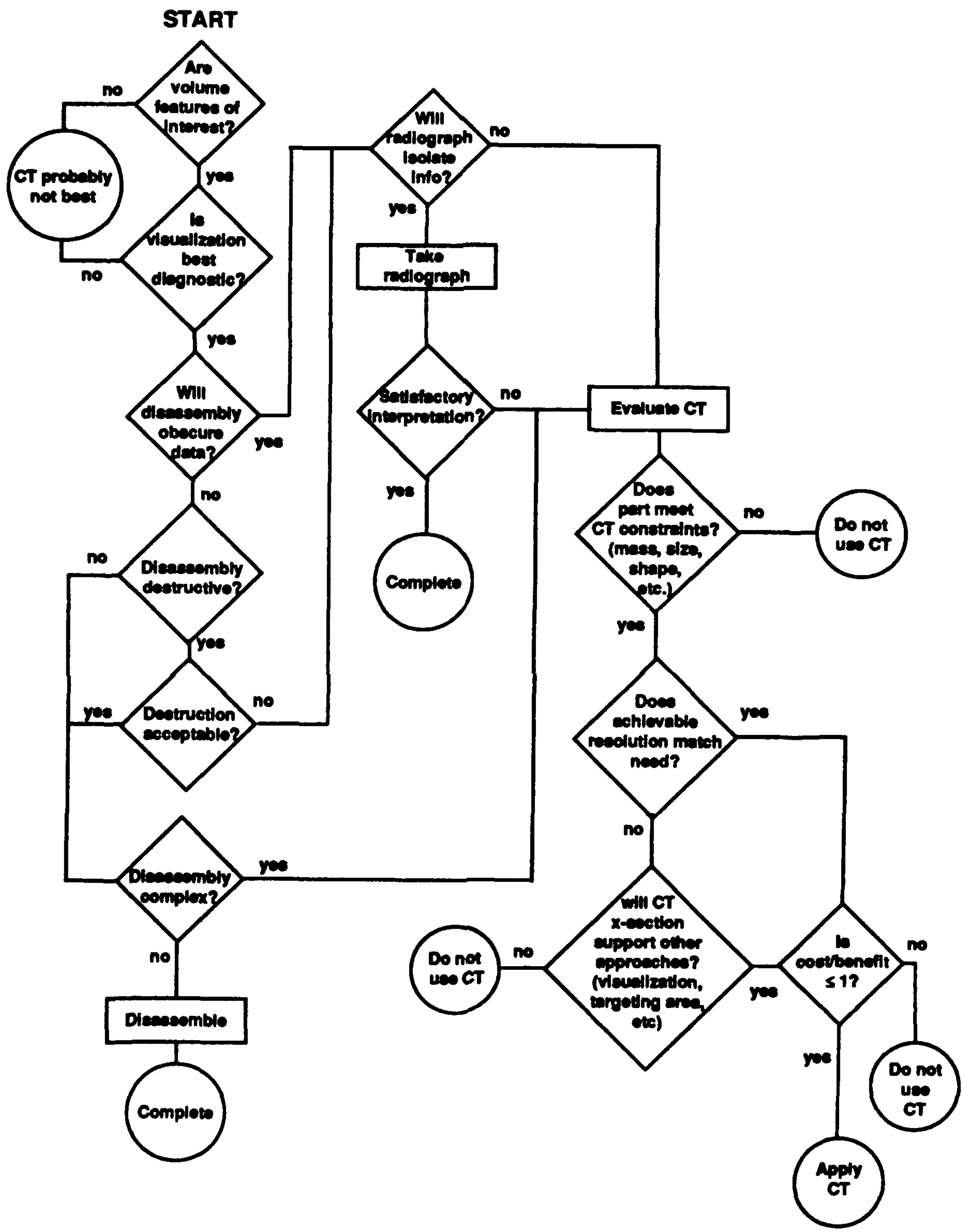


Figure 2.3-1 CT application logic flow.

3.0 APPLICATIONS EXAMPLES

The CTAD program has already identified in earlier task assignments a number of examples of applying CT to failure analysis. These were summarized in preceding sections. The program has also noted that presenting example stories is an important aspect of educating interested individuals to the technical and cost benefits of CT evaluation. This section discusses several additional examples of using CT for failure analysis investigations not previously reported. The examples include electromechanical hardware, electronics, mechanical connections, structure and materials.

3.1 DC Torque Motor

Electromechanical systems are complex in nature not only from their physical construction but also from their functional aspects and the environmental extremes that they must withstand. Failures normally require careful disassembly to determine the cause. CT provides information which enables correct interpretation of the condition.

An example of how CT can benefit the interpretation of failure in an electromechanical device is the case of a DC torque motor. The motor is used in a critical spacecraft application to operate a cable reel. It is essential that the motor perform reliably, because there is no opportunity for recovery from a malfunction. In the course of spaceflight qualification, the assembly underwent a three-axis vibration test. Following the test, it was observed that the motor current (and power) necessary to perform its function, had increased, although it was still within the allowable range for flight. The motor could not be disassembled without voiding the qualifications already passed. Application of the logic tree led to the conclusion that CT would be an ideal diagnostic to determine the nature of the motor change that had caused the power increase. It was not known initially for what to look, but it was logical to suspect the motor brushes. In fact, an initial CT cut through the brushes showed that there were no problems with them, a finding that would probably have been ambiguous if the brushes had been removed for inspection. With the brushes eliminated as a cause of the problem, additional cross sections were examined until the problem area was identified. The results are shown in Figure 3.1-1. The CT image shows that two permanent magnet poles, originally glued to the motor case interior wall at the 6:00 and 12:00 positions, had disbonded and were contacting the armature. It is remarkable that although the poles appear to be jamming the armature, the motor continued to function within allowables. It is unlikely, given all the safeguards in spacecraft qualification procedures that it would have been accepted. But one must consider the possibility that, since the motor was operating within specifications, it may have been accepted and would have almost certainly failed on mission. Use of CT prevented such an outcome without concern for compromising the qualification work that had preceded the change in performance. In this case, the motor was sent back to the vendor for disassembly with a clear knowledge and description of the problem. The CT scan made it possible for Boeing to inform its customer as to the nature of the problem immediately, eliminating uncertainties while waiting for the vendors inspection cycle. Figure 3.1.2 shows a photograph taken during disassembly which confirms the CT results. The diagonal cut from the lower pole, observed in the CT image, was the result of material fracturing out of the pole. This would also have been identified with CT if additional slices had been examined. Dislocation of the poles was the result of broaching tool wear on the cutter used to machine the shallow slots in which the poles nested. In addition, glue was improperly applied to the poles so that there was little wetted contact in the bond to the motorcase. Although the specific cause of the problem was isolated visually, CT could have identified these deficiencies if more extensive imaging had been done.

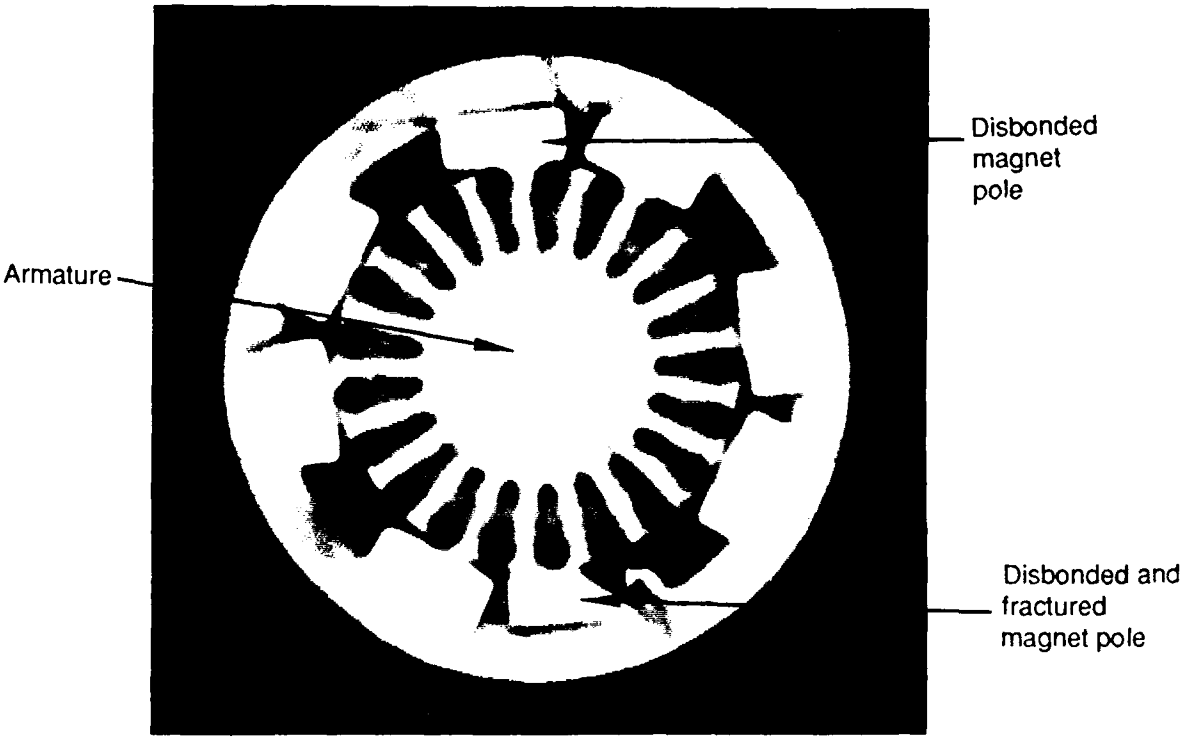


Figure 3.1-1 CT image of internals of a DC torque motor.

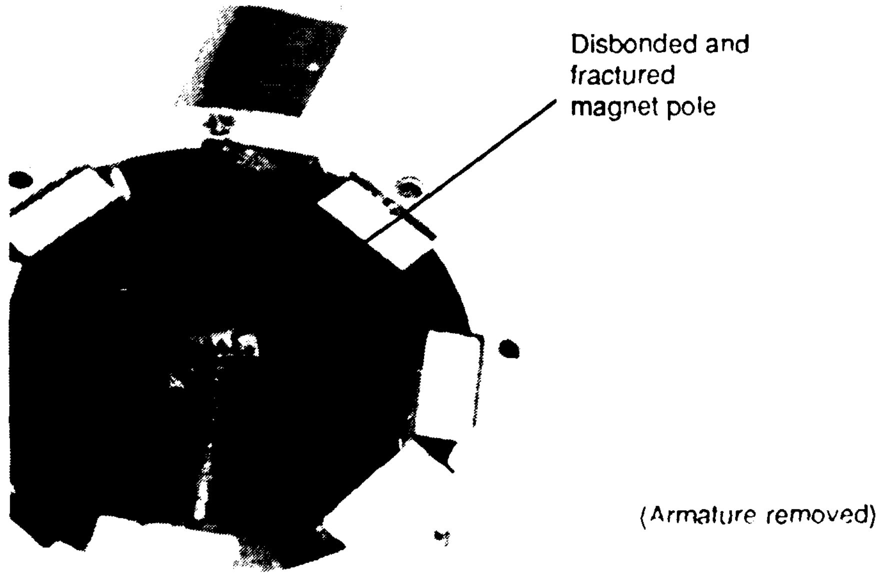


Figure 3.1-2 Photograph of torque motor during disassembly.

Several cost benefits were associated with this investigation. The ability to quickly and nondestructively determine the cause of the excess motor power held the potential for assuring confident use of the motor, if no problem was detected, without incurring extra expense for requalification (~$30K). In this case, the investigation led to rejection of a part that was functioning within original allowables, and identification of a common problem among a manufacturing lot of motors. This saved the cost of qualification of additional motors which would likely have been rejected at a later stage in spacecraft preparation (installation + qualification +cost of rejected motor ~$35K). In addition, it prevented use of the motor under circumstances where it would have been likely to fail during the spacecraft mission. The attendant cost savings would be the cost of the spacecraft and the launch, not to mention the value of the mission data that would have been lost. The spacecraft engineers also pointed out that it had been very important to them to be able to use the CT data to communicate the problem to their customer immediately; the value of good customer relationships, while hard to quantify, is very real.

3.2 Relay

Electrical components have a full spectrum of mechanical aspects and properties in addition to their electrical/electronic properties and characteristics. Many of these mechanical aspects can be responsible for a failure, such as bond wires, die attachment, die layout, packaging defects, contaminants and others. Due to their complex mechanical nature and small size, relays are difficult to analyze. Radioscopy (real-time radiography) has been used with limited success. The presence of large amounts of Fe, Cu and Pb with the superposition of parts often inhibits the abilities of radioscopy to detect problems internally. Often, it is necessary to open the relay can or section it to evaluate a failure. This often obscures the cause of the problem, such as contact-arm rubbing on the case.

During this task, a relay (see Figure 3.2-1) was submitted from the PEFA laboratory that had been given to them for failure mode verification. The relay was one of a batch that exhibited defective closure of the normally open contacts on one side. Owing to earlier analysis of similar units, it was believed that the defect was caused by an internal hold-down strap which was detached from the base. The hold-down is necessary to resist the armature forces during relay operation so that the contacts could be driven closed. In the absence of the restraint, the armature can rock back and the contacts will not undergo full travel. Although there was good, circumstantial evidence of the failure mode, it is the PEFA laboratory responsibility to physically verify failures on all parts submitted. Therefore, they anticipated 2 to 3 hours of processing to mechanically disassemble each unit they received for inspection. The time commitment would be increased if there was doubt as to the failure mode because disassembly and/or sectioning would have to be very slow and precise to avoid possible destruction of the evidence for the failure.

Radioscopy had been tried with these parts and it was found that failure of the hold-down straps could be detected if the view was carefully adjusted, but the procedure was tedious and somewhat hit-and-miss.

Again, this relay appeared to be a good candidate for high resolution CT on the basis of the logic tree of Section 2.3. CT slices were made to step through the suspect hold-down straps on both sides of the relay assembly. Figures 3.2-2 and 3.2-3 show CT slices from opposing sides, on one of which the strap is properly secured (Figure 3.2-2) and the other of which the strap is unbonded. The straps have an extension tab that extends down over the base. When the assembly is properly seated, the shoulder on the strap rests on top of the base and the tab extends over the side and is spot welded. In a properly secured assembly, there should be no gap between the shoulder and the base (as is the case in Figure 3.2-2). Figure 3.2-3 has an obvious gap confirming that the spot welds have failed, as suspected. Figure 3.2-4 is a photograph of another relay in the series that

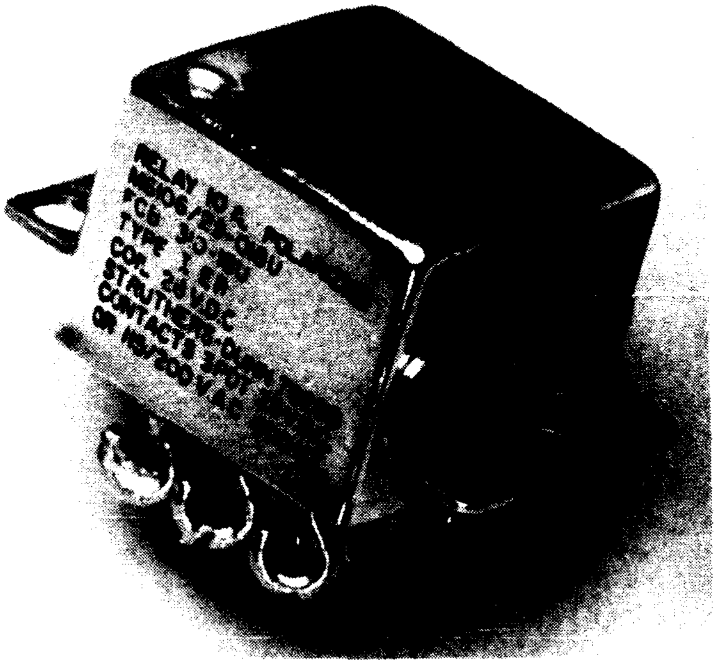


Figure 3.2-1 Photograph of failed relay.

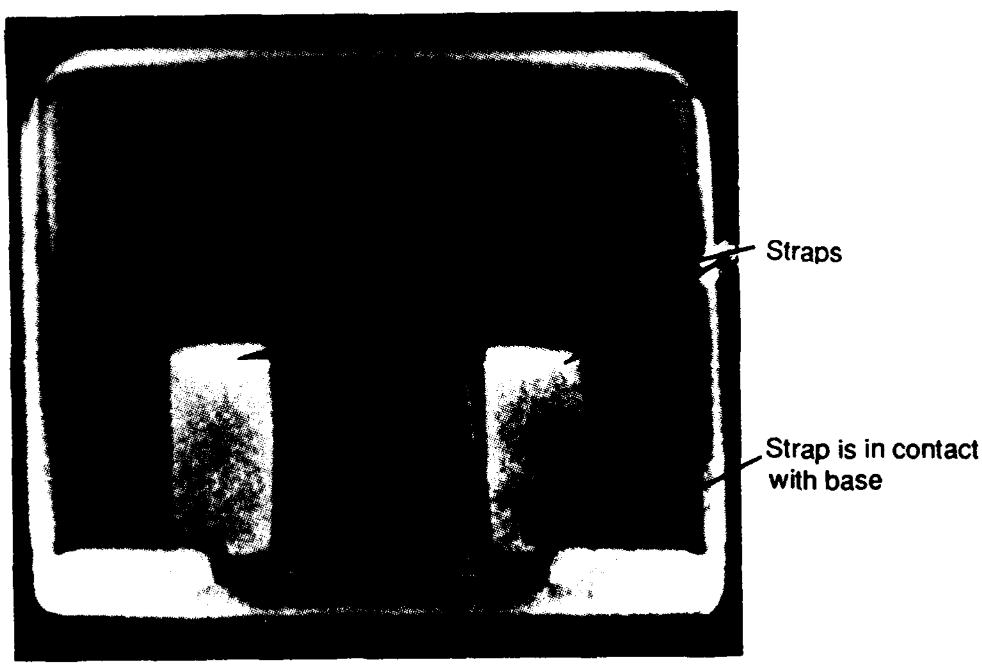


Figure 3.2-2 CT slice through the internal hold-down strap of a failed relay showing properly located strap.

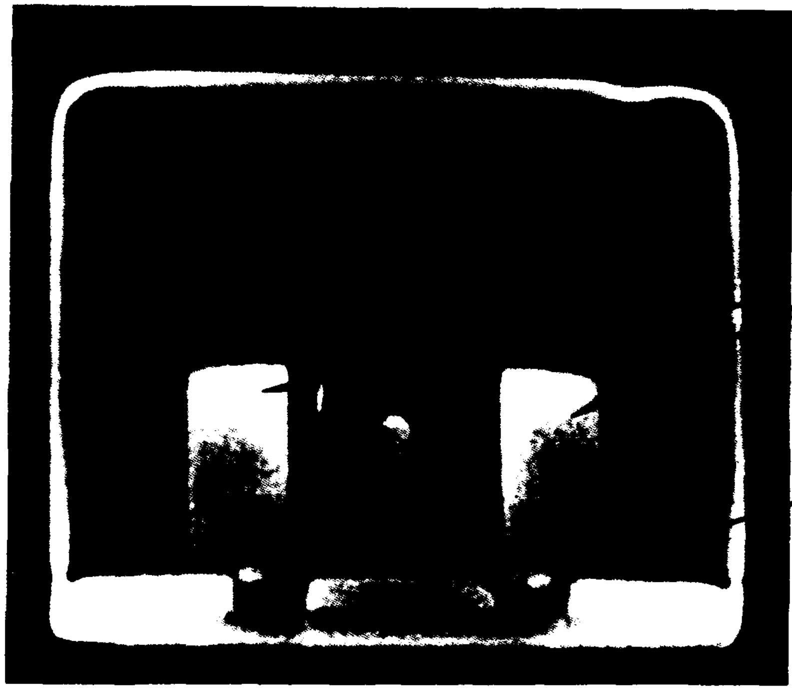


Figure 3.2-3 CT slice through the internal hold-down strap of a failed relay showing detached strap.

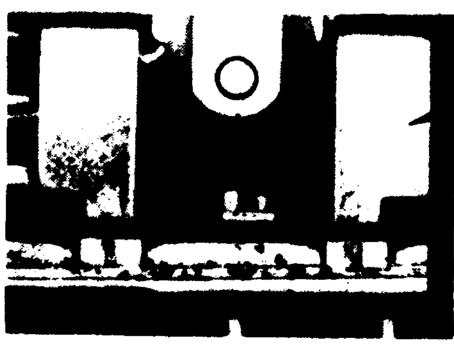


Figure 3.2-4 Photograph of a disassembled relay showing detachment and offset of the hold-down straps detected with CT.

has been sectioned. It shows the failed spot weld and offset of the straps (larger in this case) that was identified in the CT scans. The CT scans can be obtained in roughly 30 minutes on a single part if the laboratory has direct access to the small, high resolution scanner required for this type of evaluation. A batch job should take less time per part. Thus, the labor savings, using CT is about 2 man-hours per relay, when the probable failure cause is known, and can be considerably more if physical sectioning would be otherwise required.

3.3 Quick Disconnects

Mechanical devices depend on the materials selected, structural design, dimensions used, and proper assembly to achieve the desired application. Both macro and micro details are important. CT can be used as an investigation tool capable of supporting failure analysis and evaluation by providing dimensional, density and defect information. This can be accomplished at the macroscopic level on complete assemblies and at the micro level on reduced size specimens.

Figure 3.3-1 is a line drawing of an assembled, miniature, quick-disconnect fitting used to connect the pilot's breathing air from the aircraft supply to his helmet in many military aircraft. In the event of ejection, the pilot is required to release the fitting so that certain equipment can be discarded from the ejection hardware prior to his landing. Release is effected by a simple pull on the connector which is designed to remain engaged under normal operating pressure but disengage with a pull force between 12 and 20 pounds. However, a large batch of connectors was delivered that would not release with forces as high as 100 pounds. The malfunction depended on the mating orientation and was not the same in every unit. Boeing project personnel were directed by their customer to understand and correct the problem under tight budget and time constraints.

A series of mechanical measurements were made to quantify the problem which did not reveal the cause. One of the difficulties was an inability to visualize the precise fit-up of the parts when assembled. It was known that the disengagement force increased if the pull was not directly on-axis for the male plug. The required force seemed to correlate with the clocking of a split, snap-ring on the leading portion of the plug (this supplies the retention force by friction with the tapered retention gland), and some connectors exhibited too little retention force. It was conjectured that the plug could axially misalign sufficiently to produce increased frictional force at the retention gland, and that the connector was bottoming out prior to full engagement. However, owing to the small size and rather subtle defects, it was difficult to test the hypotheses with dimensional measurements alone.

The connectors were brought to a medium resolution CT facility for nondestructive sectioning of the assembled unit. Figure 3.3-2 shows an axial CT slice through two assembled connectors, and one plug, on their centerlines. The bright segment on the plug is the snap-ring which is meant to seat well up on the mating entry ramp of the socket. The resolution of these slices is insufficient to detail the fitting tolerances, but it did establish that the plug penetration and seating of the snap-ring were proper. Figure 3.3-3 shows a CT slice transverse to the assembly at the snap ring. The gap in the ring is clearly visible at 12:00. These views were studied with different clocking of the gap to see if snap-ring engagement or compression was visibly different in different orientations.

This case is one in which CT did not yield the answer to the failure problem directly although use of a high resolution machine would have provided more precise dimensional information that very likely would have led to earlier identification of its cause. The value of CT was that visualization of the assembled unit helped eliminate a number of hypotheses and focussed attention in directions that eventually led to correction of the problem. The root-cause of the problem was traced to failure by the snap-ring manufacturer to maintain quality control adequate to the rather tight tolerances of the assembly. Accumulated errors could result in a near-interference fit of the snap-ring in the assembly, or sufficient sloppiness that axial offsets and/or loose fits would occur. The team investigating the problem judged that several additional man-weeks of effort would have been

team investigating the problem judged that several additional man-weeks of effort would have been required to converge on a solution in the absence of the understanding gained by examination the CT data. Capability for obtaining different internal views of the device as questions developed was also judged to be extremely valuable. The total time spent in the CT investigation was about half-a-day by several QA engineers and the CT system operator.

The benefits associated with CT were twofold. Saving several man-weeks of investigation had a direct monetary return estimated at $10K. In addition, rapid solution of the problem was demanded by the customer. CT helped to meet this important objective, and provided in-process visualization which was very important in keeping the customer informed of progress.

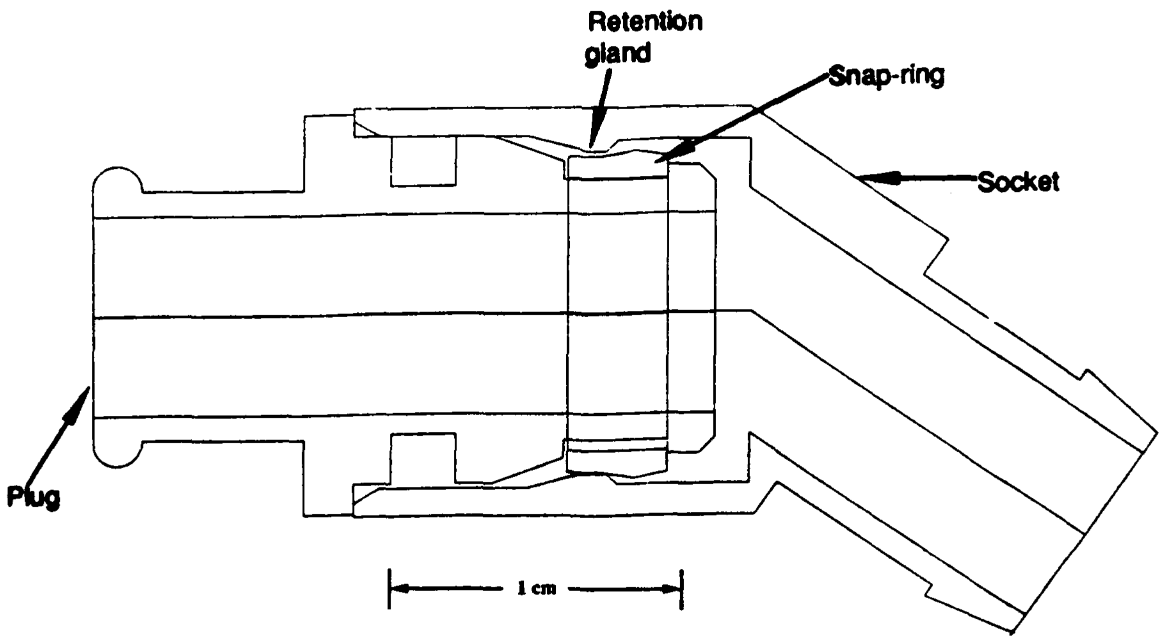


Figure 3.3-1 Line drawing of assembled miniature quick-disconnect assembly.

Figure 3.3-2 Axial CT slice of miniature quick-disconnect on centerline.

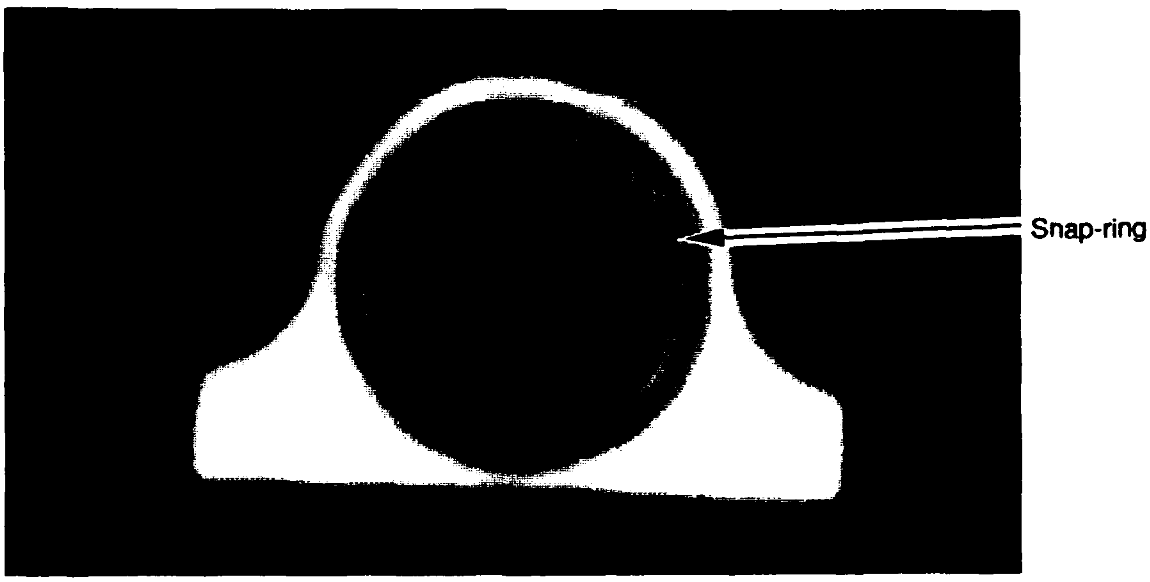


Figure 3.3-3 Transverse CT slice through the snap-ring of an assembled unit.

3.4 Failure Analysis of Spoiler

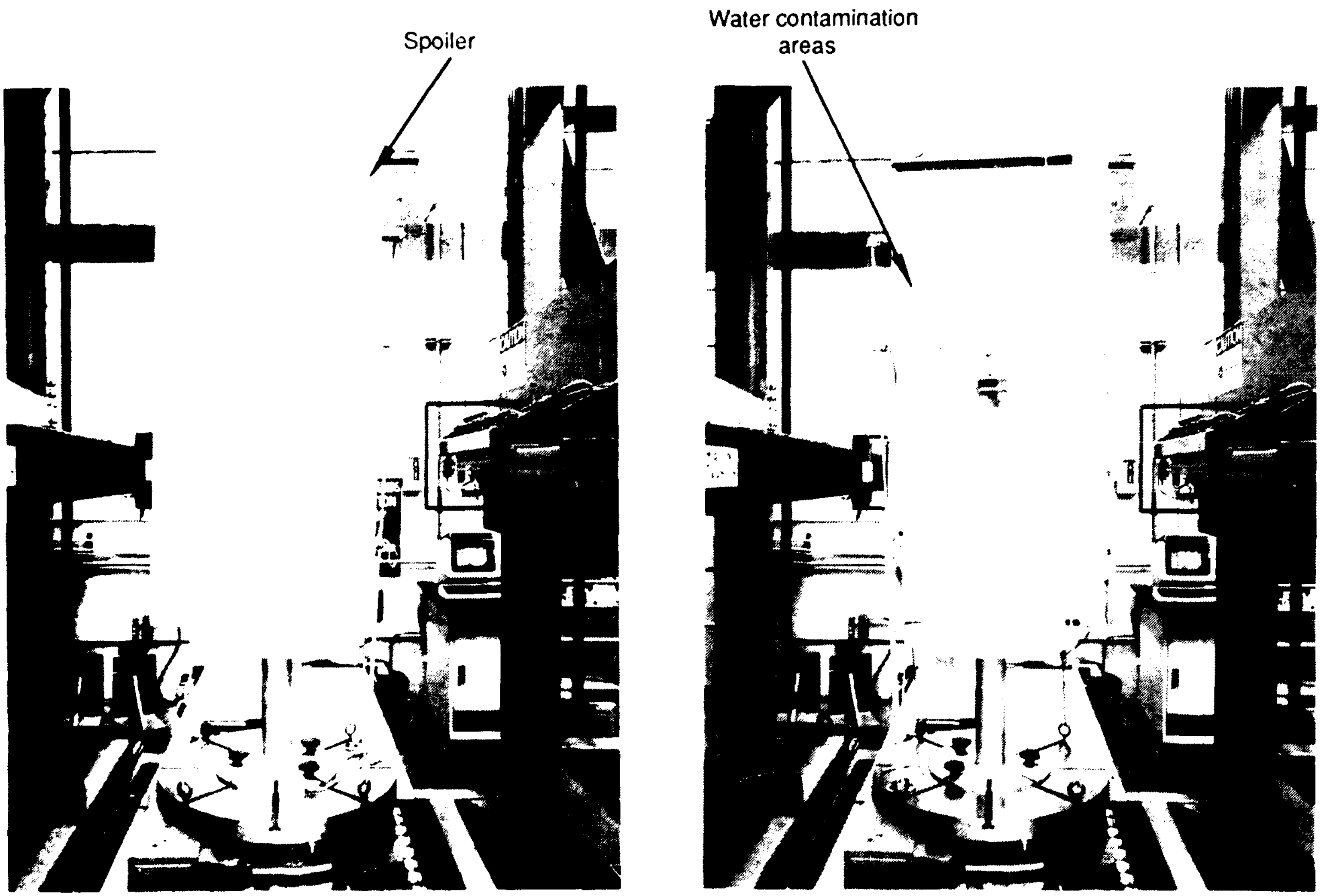
Because it may be one of a number of possibilities, the cause of failure in complex structures (such as some composites and other advanced materials) is usually determined through time-consuming and costly evaluation methods such as destructive sectioning, microscopy, and chemical analysis. CT can be a supplemental evaluation tool, and in some cases, an alternative tool for destructive failure analysis of materials. It provides the capability of examining the interior of a material system before or in lieu of destructive sectioning, and allows quantitative measurement of dimensional and density information.

As an example, the graphite epoxy composite, Nomex honeycomb aircraft spoiler shown in Figures 3.4-1a and b, was evaluated with CT cross sectional imaging inspection after digital radiographs (obtained on the CT scanner) had confirmed the presence of liquid water in some of the honeycomb cells. Areas in which water had been observed are indicated by approximate bounding curves drawn on the panel, particularly on the underside. The area around the actuator fitting and hinges appeared to be particularly affected. The water apparently accumulated over an extended in-service period. It was of critical interest to establish the level of contamination and the path(s) by which the water entered. Standard radiography did not provide this information, and destructive sectioning may very well have obscured the information, particularly if there was no record, such as CT images, to guide the investigation.

CT has several attractive attributes in this application. Since it basically produces a volume density distribution map of the part, it can distinguish water from the composite material and adhesives used in the assembly. Therefore, it is possible to quantify the amount of water in individual cells, both visibly and by numerical processing, and to trace water pathways along interfaces (for example) if the water volume element size is a reasonable fraction of the resolution volume of the CT scanner.

Figure 3.4-2 shows a portion of a digital radiograph of the spoiler which includes the region around the actuator fitting and the central pair of hinges. The panel is internally complex. The center section contains large honeycomb cells,and an inlet section, containing no honeycomb to provide space for the hydraulic actuator. Reinforced face sheets distribute the actuator loads. This section is joined to one using a much smaller honeycomb separated in both the vertical and horizontal planes by internal septums. Inserts are also included to support and fasten the actuator fitting and the hinges. It is clear from the digital radiograph that many of the cells contain water, and it can also be determined from the data values that the quantity differs from cell-to-cell. Because the aircraft flies at high altitude (>30,000), it is expected that the water undergoes frequent freeze/thaw cycles, and the panel can also be partially evacuated on every flight cycle if pathways are open to the atmosphere. Thus a mechanism is available for ingestion of moisture, and migration from cell-to-cell may be promoted by freeze damage to cell walls. The fact that water generally radiates away from the hinge inserts and/or the septums suggests that it may enter at these features, but this cannot be established unambiguously.

CT slices were prepared at numerous planes normal to each of the three axes of the spoiler. Two vertical cuts through the radiograph are shown in Figures 3.4-3 and 3.4-4. Figure 3.4-3 is a slice just above the septum in the top of Figure 3.4-2 (A-A'). Figure 3.4-4 is a slice at (B-B') through the water concentration below the actuator fitting. It includes the roll-off from the honeycomb to the actuator well. They show that considerable water contamination of the cells has occurred ranging from about 10 to 100% of cell volume. Determination of the degree to which water fills the cells is important to understanding whether freezing could be expected to damage the cell walls or debond the face sheets. Quantification of the water is simply done by measurement from the image, or use of numerical image processing techniques. It is not clear, from the sample slices, what the water pathways are although the distribution of water in



(a) (b)

Figure 3.4-1 Upper (a) and lower (b) surface views of a composite honeycomb spoiler (1.5m tall and 0.7m wide) in which water contamination had been identified. (Spoiler is mounted on a CT scanner.)

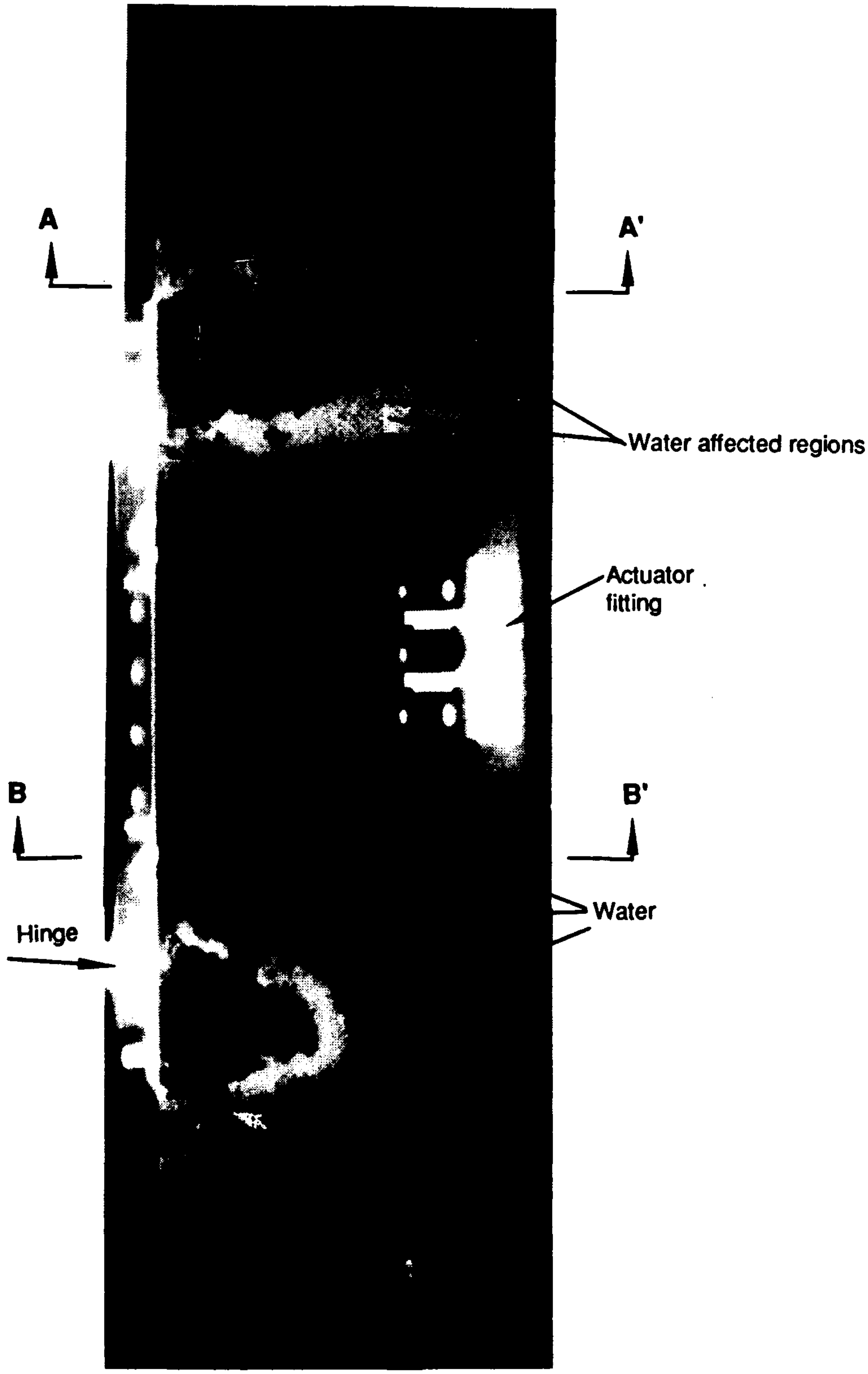


Figure 3.4-2 Digital radiograph of the center section of a spoiler showing honeycomb cells with maximum water contamination.

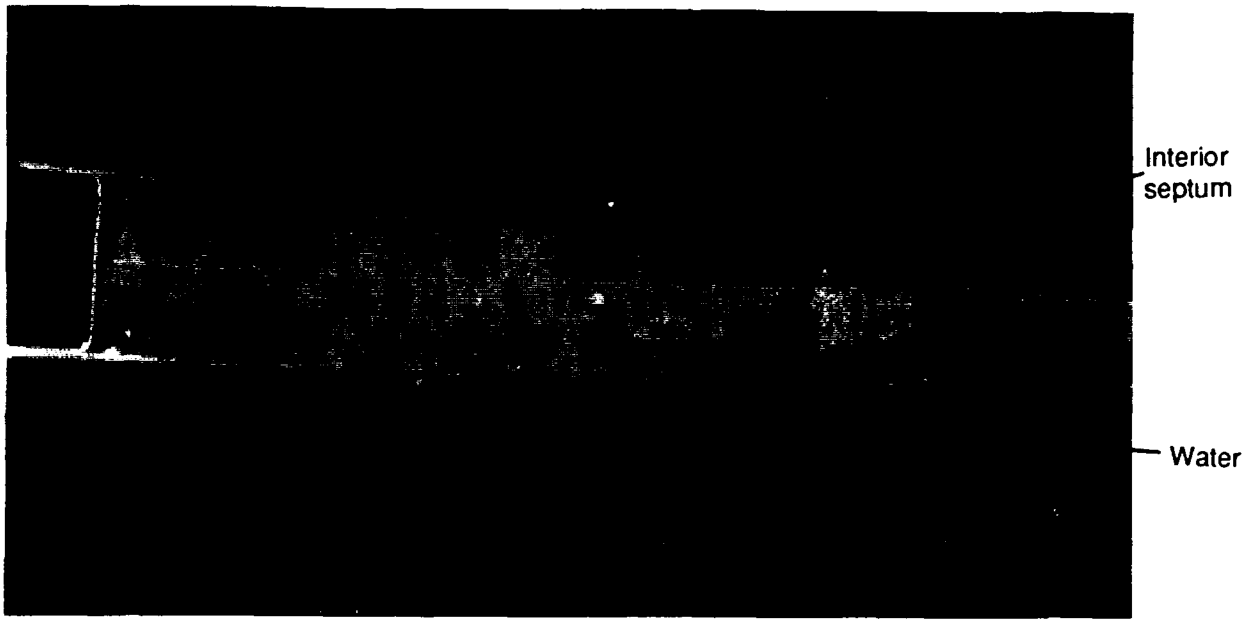


Figure 3.4-3 CT slice through the spoiler at the plane A-A' shown in Figure 3.4-2.

Figure 3.4-4 CT slice through the spoiler at the plane B-B' shown in Figure 3.4-2.

Figure 3.4-3 suggests possible migration along the horizontal septum. If cell damage has occurred, it cannot be identified in the CT slices at the available resolution (> 0.25 mm).

It was possible to step through the septums, by combining sequential slices of the panel into a 3-D volume set. The 3-D data were viewed in each of the three axes to examine the neighborhoods of all suspect internal structures for possible water pathways. Unfortunately, the water contamination mechanisms are complex, and probably subtle. Stepping through internal structures did not prove or disprove that water migrates along them. If water enters because of the depressurization/repressurization cycles of flight, it may arrive as vapor that subsequently condenses. Cell-to-cell migration may also be slow, through minor cracks or disbonds resulting from repeated freezing cycles. Therefore, there may not be a "marker" left in the migration routes that can be easily identified in a static measurement. Additional understanding of the problem might be gained from CT measurements during partial evacuation, or on a frozen panel as it thaws, but it was decided that panel sectioning, with the help of the CT images was the best follow-up course for this investigation.

Much of the information gained in this case was derived from the digital radiographs which confirmed the water contamination of the spoiler and gave an overall picture of its distribution as well as hints as to the points of entry. However, CT was required to establish the quantity of water and provide views of the way it was distributed, top-to-bottom in cells and along the internal structures. Because proper sectioning of complex composite structures is tedious and difficult, and because the sectioning often alters the internal environment of the part, it is very important to have a clear picture of its undisturbed condition before beginning any sectioning. This is the principal contribution of CT in this case. It provides information that may be essential to proper interpretation of sectioning data, and that cannot be obtained in any other way. It is difficult to associate a direct cost savings with the use of CT in this instance, but it may make the difference between success and failure in a failure analysis procedure that will involve hundreds of man-hours. In addition, the ability to apply state-of-the art technology to the resolution and correction of this type of problem has very high value to customers in a highly competitive market place.

It is useful to note that the digital radiographs were acquired on the CT scanner. They are particularly desirable because of their large field of view and wide dynamic range. This makes it possible to examine large structures in detail, and to emphasize different density features from a single radiographic record. Note also that although the spoiler has a large aspect ratio (width/thickness), useful CT slices were generated on all three axes of the part.

3.5 Composite Damage Analysis

The assessment of anomalies in composite structures can be difficult. If destructive analysis is performed for assessing damage, then each layer of the composite must be carefully removed and the surface photographed to determine the extent to which each layer is disrupted. An example of the use of CT to support damage analysis is the evaluation of crack formation at fastener holes in a composite. A test sample, sectioned from a larger panel to fit within the test volume of a high resolution CT scanner, is shown in Figure 3.5-1. The sample coupon is 25 mm (1 inch) in diameter and 17 mm (0.75 inch) tall. It is a graphite epoxy laminate consisting of 86 plies with an 8-mm-diameter (0.3 inch) hole through it. The layup uses 0, 45, 90, and 135 degree ply orientations in a special sequence. The sample was fabricated for destructive stress testing. A fastener, inserted through the hole, was statically loaded to produce internal damage and then removed. The hole was then filled with radio-opaque penetrant (a zinc oxide mixture) for 30 minutes to infuse any cracks or delaminations. The cracks and delaminations that absorb radio-opaque penetrant will be detected with radiography. However not all defects absorb the penetrant and, therefore, go undetected in the radiograph. CT examination measures local densities both above and below the nominal and is more sensitive to the defects than radiography as a result. CT shows both the radio-opaque (bright) and void (dark) regions of the sample.

Radiographic examination of the test sample can confirm damage and indicate its extent, averaged over the sample thickness, but it does not provide a 3-D map of delamination and cracking patterns. High resolution CT scanning was performed for this purpose, breaking the height of the coupon into 200 images in steps of 0.09 mm. Figure 3.5-2 shows a series of reconstructions (images 12-to-23) of the CT data normal to the hole axis. The field of view is 30 mm and the image uses a 512x512 pixel array. Slice thickness is estimated to be 0.18 mm at the sample. The ply orientations are clearly discernable as the CT reconstruction effectively peels sequential layers from the composite. Anomalies that are void (dark) or filled with penetrant (light) are also visible. Figure 3.5-3 shows a similar collection of cross-ply slices that progress through the hole in the sample. Delaminations are identifiable in this series.

Materials engineers are interested in the overall pattern of cracking and delamination in order to understand stress distributions and damage response in composite structures. This information is useful for modifying materials and layups to produce improved structures. Therefore, it is of interest to produce 3-D maps of the damage patterns. While this might be possible using conventional sectioning, it is obviously extremely tedious, and damage done in sectioning may obscure the desired data. With CT sectioning no sample alteration results and the data are digital, which lends itself to powerful processing algorithms that can isolate the defect structures from the background of undisturbed material. This is illustrated in Figure 3.5-4 which shows the results of numerical processing to extract features that are above (filled defects) and below (unfilled defects) the local background density of the undamaged composite. This anomaly extraction was accomplished with "grayscale mathematical morphology" using an approach known as "grayscale opening residue" [15]. This technique effectively constructs an image of the undamaged material by operating on the bright image areas to correct them to the neighborhood values (it does not correct to global values). The image constructed in this way is then subtracted from the original to leave a "residue" containing only the anomalous values. Since this does not correct for dark areas, a similar process is followed for the negative image. The combined result contains a map of all anomalies isolated from background material. The two sets of residue data (light and dark) are further processed to identify cracks and delaminations. This is done by recognizing that when slices are made cross-ply, delaminations tend to produce horizontal line segments. Cracks tend to produce roughly vertical line segments unless they happen to fall in the plane of the slice (in which case they produce an area feature). Processing of the residues with algorithms that recognize horizontal or vertical line segments that are in either the light or dark data set discriminates for crack-like or delamination-like features. Ambiguities resulting from the fact that cracks are not constrained to known planes (as delaminations are) are removed by processing orthogonal sets of slices. Additional discrimination is obtained by also selecting for line segments greater than a threshold length and requiring that crack-like features extend through more than one ply. This step produces eight anomaly volumes that are then combined into a single volume classification. The result is the processed image of Figure 3.5-4 which successfully highlights only damage elements of interest. It can be appreciated that additional data filtering could be conceived to further isolate particular damage features.

The above discussion highlights CT's benefit as a very powerful analytical tool for materials development. The results emphasize information of direct interest to materials engineers that could not have been collected economically by any other technique.

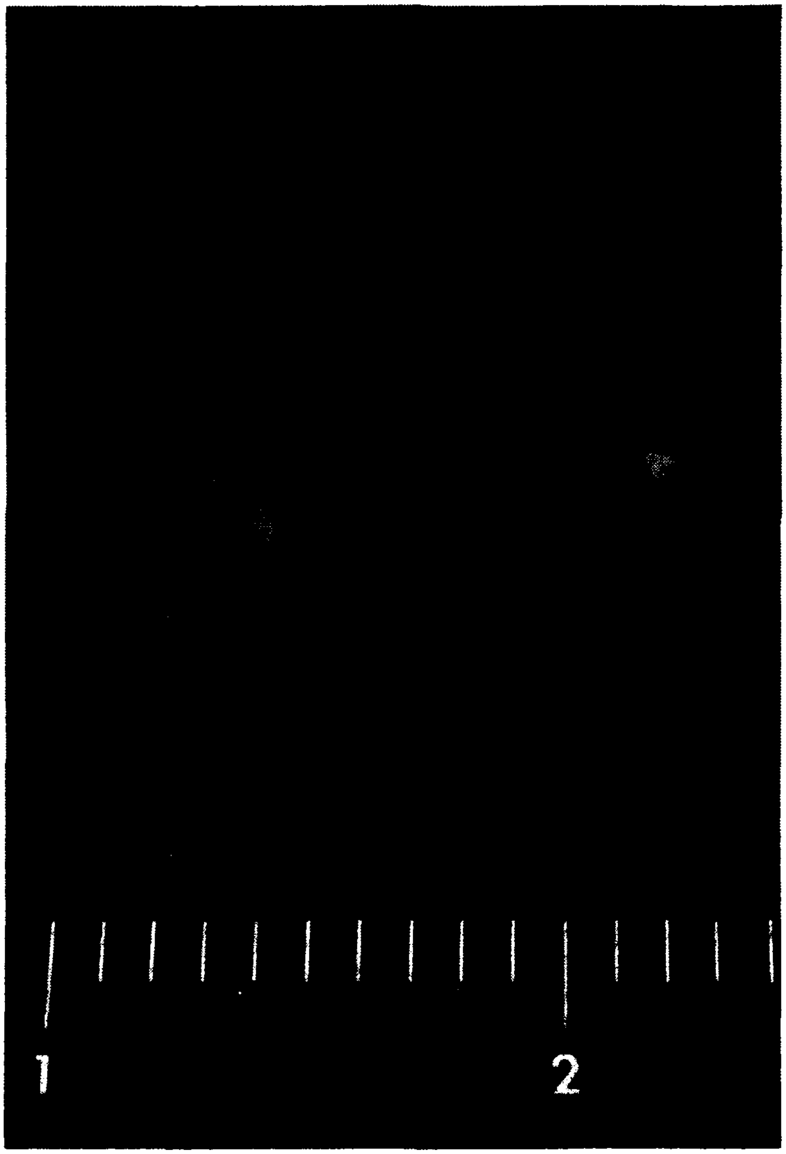


Figure 3.5-1 Photograph of the graphite epoxy composite sample.

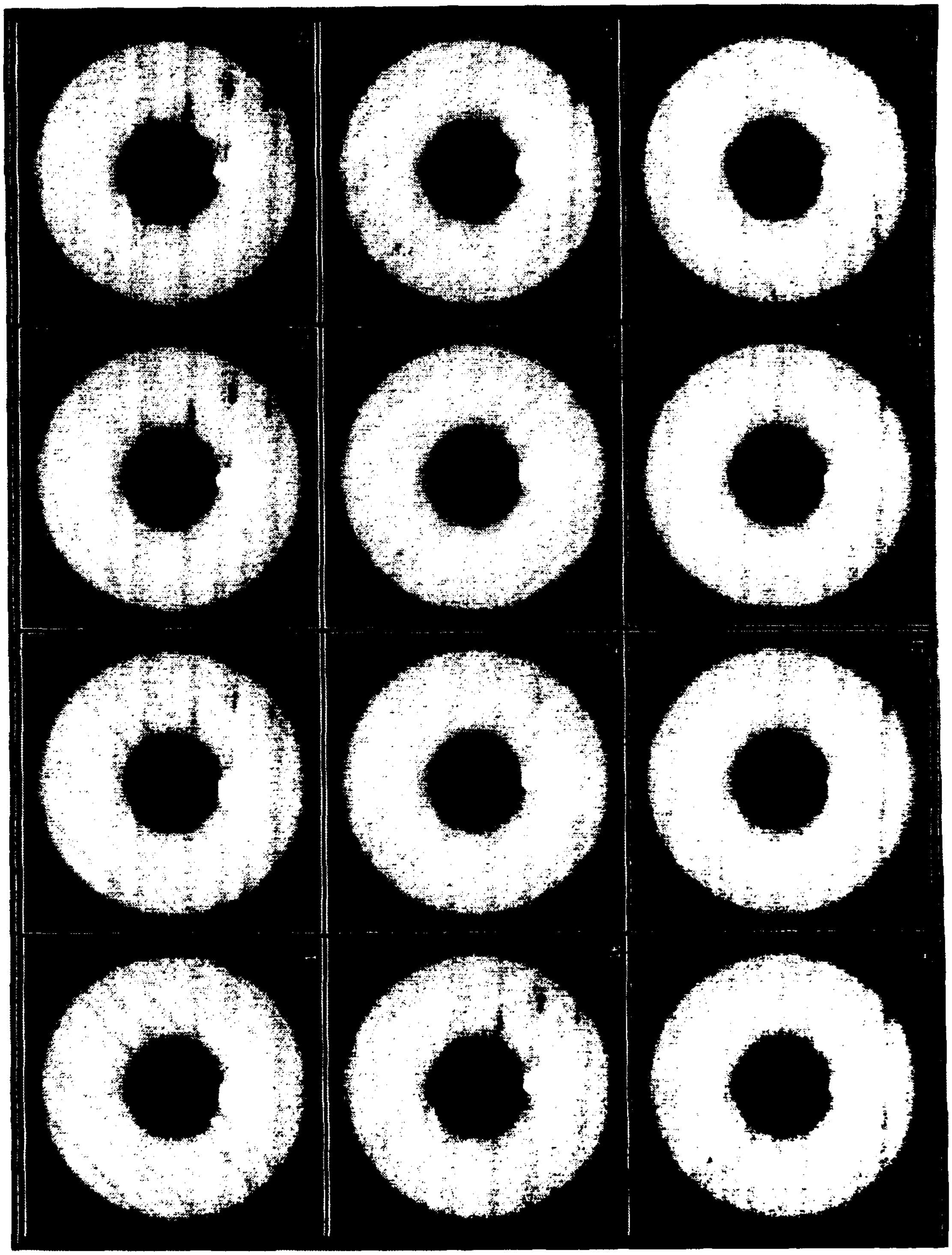


Figure 3.5-2 Series of CT slices through the graphite epoxy composite sample, normal to the hole axis.

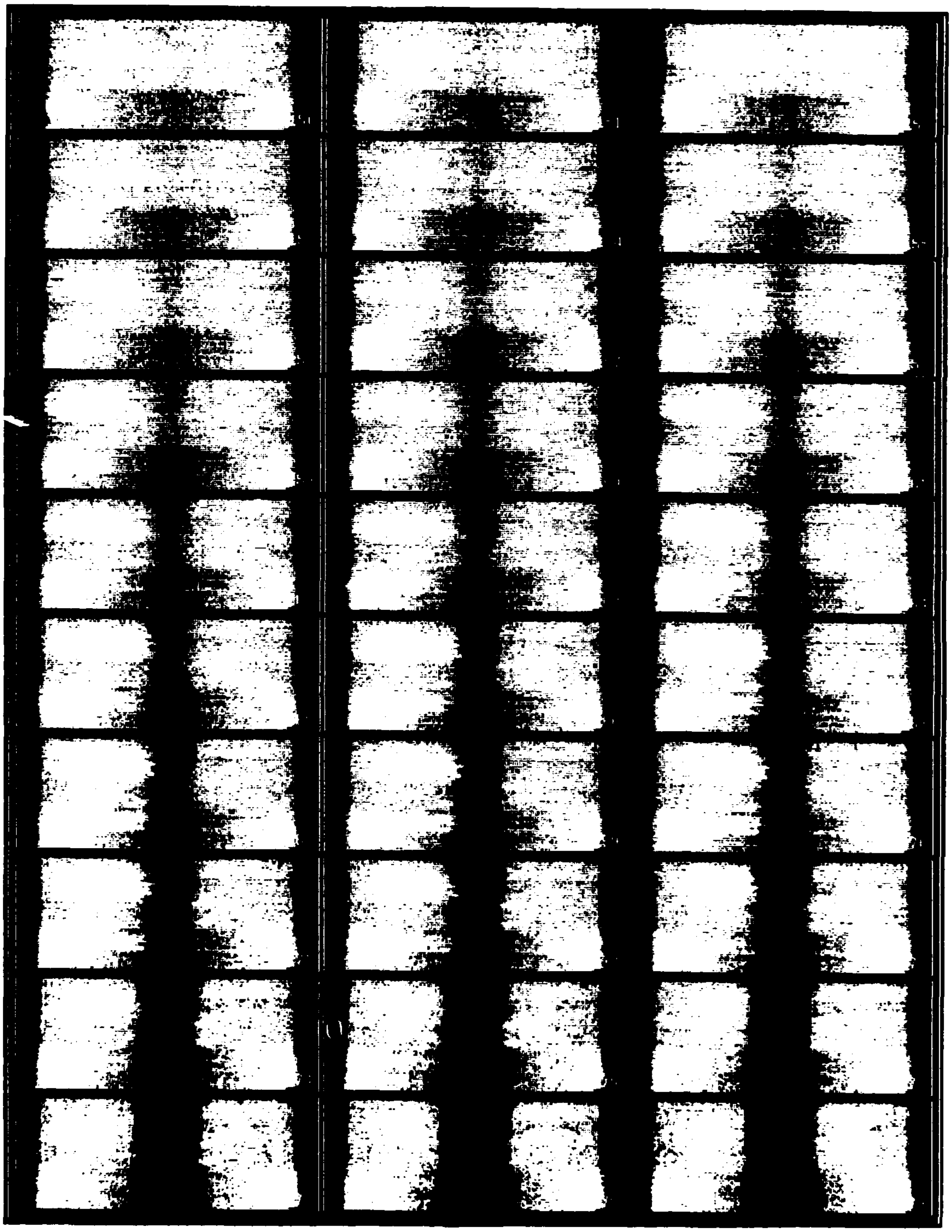


Figure 3.5-3 Series of CT slices through the graphite epoxy composite sample, parallel to the hole with slices progressing through it.

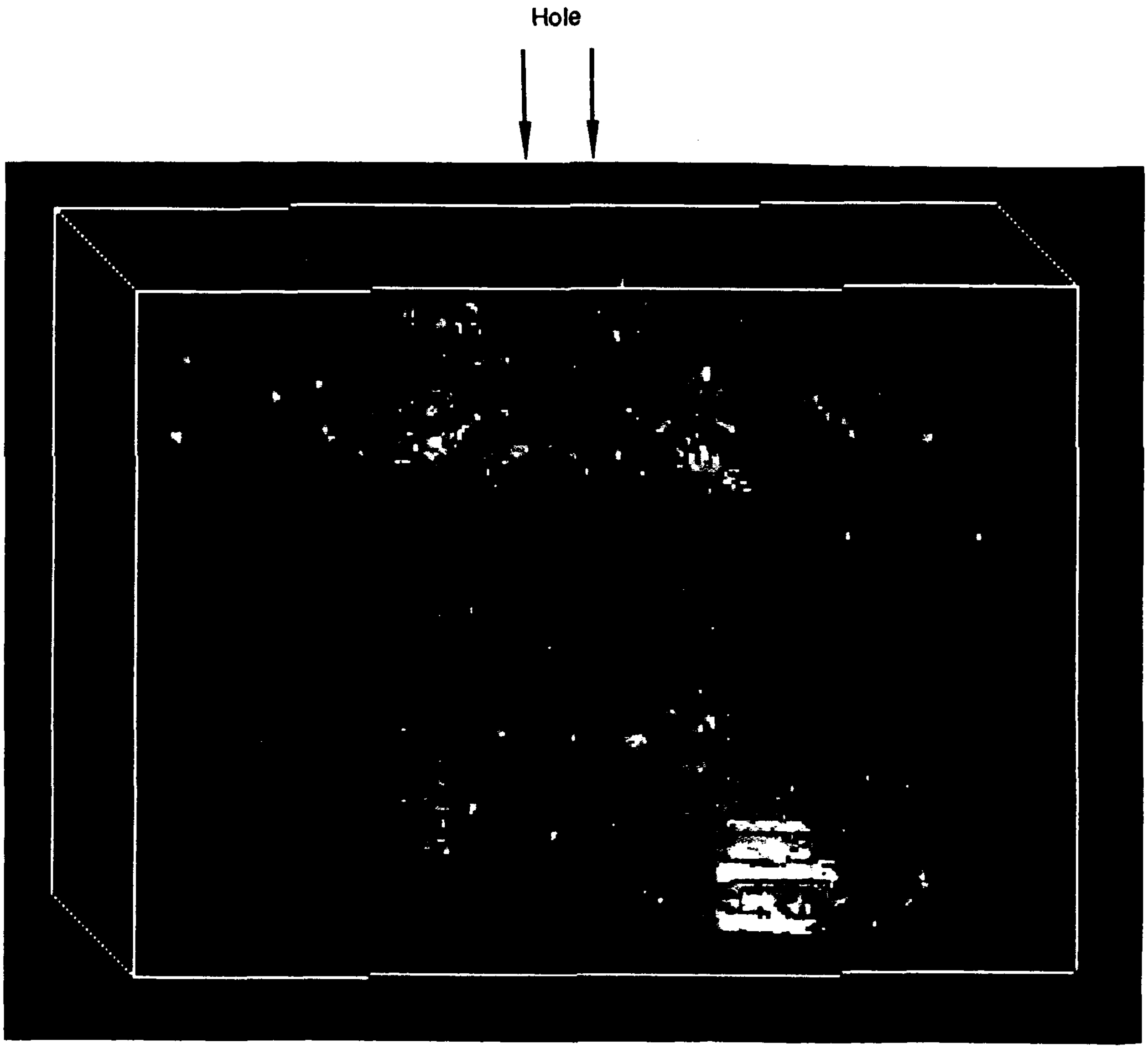


Figure 3.5-4 3-D image of anomalies in damaged graphite epoxy isolated with mathematical morphology.

4.0 BENEFIT ANALYSIS

4.1 General Benefits

Benefits of CT to failure analysis have been demonstrated in this program that are as varied as the failure analysis problems investigated. Technical benefits have been identified in almost every case, even when CT was not able, by itself, to resolve a particular failure analysis. Table 4.1-1 summarizes the benefits identified with CT in failure analysis and product development not directly associated with cost. Unfortunately, technical benefits are not easy to quantify in costs terms.

Table 4.1-1 CT Benefits for Failure Analysis

Benefit	CT Value Added
Permit previously impossible parts evaluations	Extends the effectiveness of failure analysis activities and makes resolution of unknown parts malfunctions possible. Eliminates "hit and miss" approach to failure cause isolation.
Direct failure identification without part modification	Preserves evidence of failure. Replaces more costly, disassembly and or sectioning procedures.
Provide as-is record of part before disassembly	Provides record of part condition in failed configuration as reference to understand physical evidence resulting from inspection procedures.
Provide adjunct guidance in disassembly or sectioning	Shows relationships of assembled components and identifies best paths for disassembly procedures.
Provide guidance for further tests on same or related parts	Allows visualization of internal condition of parts under test that can be used to plan and execute additional tests or perform modified tests on additional samples.
Identify suspect but acceptable, functional parts without compromising integrity or prior work	Provides noninvasive means of identifying cause of parts performance within, but not centered in design envelope. Makes parts salvage feasible without potentially destructive examinations and preserves high-value prior work such as qualifications.

Table 4.1-1 CT Benefits for Failure Analysis (Cont.)

Benefit	CT Value Added
Reduce risk in parts applications by providing internal visualization	Enhances quality assurance capability by making it possible to perform internal inspections on parts prior to use or in situ on a routine basis. QA does not have to be based on lot samples.
Provide management and customer understanding of parts performance issues	Provides easily understood visualization of parts and materials, often very quickly to enhance communications with customers. Aids in making informed decisions on a timely basis.

4.2 Application Specifics

The three-dimensional spatial details of internal configurations of assemblies that can be obtained with CT is very useful for nondestructive failure analysis investigations but has application specific criteria for implementation. CT was found particularly advantageous for complex systems, where radiographic images, for example have too much overlapping detail to permit easy interpretation, and for composite failure studies where existing evaluation techniques require very tedious dissection. Applications involving testing under system operational or environmental conditions were also found to benefit from CT. Review of the work load of two Boeing failure analysis laboratories indicated that CT would have a quantifiable economic benefit for approximately 10% of mechanical/electromechanical failure problems and about 30% of electronics related cases. It was also recognized that if CT were available, on the basis of the economic justification above, it would be very likely applied, usefully, in a significant number of additional cases for which intangible benefits are clear although economic benefits may not be easily defined. Table 4.2-1 summarizes conclusions of this investigation. It identifies four classes of failure analysis tasks that benefit from CT and identifies the CT system and data processing capabilities required for maximum effectiveness in each.

Table 4.2-1 CT Applications in Failure Analysis

Application	Benefit	Resolution	Remarks
Electronics Parts	Routine examination of packaged discrete components. Low utility for ICs	≥ 0.1 mm	Combination of real time radiography with micro-CT may be best approach.
Electro-mechanical	Improves reliability of failure analysis. Visualization of assembled systems valuable tool supporting traditional methods.	0.25 mm @ ≥ 400 kV	Ready access to CT is key to usefulness. Large and small parts may require multiple machine access.
Materials Development	Excellent tool for in situ analysis of often subtle internal features. Replaces less effective sectioning techniques.	≥ 0.05 mm	3-D imaging significantly enhances analysis. Numerical data processing adds significant analytical utility.
Structure Evaluation	Internal distribution of features or material conditions in large structures.	0.5 mm, >400 kV.	Ability to handle structural components >300 mm.

The largest application for CT in failure analysis studies appears to be to electronics and electromechanical systems. Failure analysis studies in these areas require, predominantly, high resolution CT systems for relatively small (less than 50-mm diameter) components. For the parts mix typical of Boeing (and probably other medium-to-large aerospace companies), laboratory workload >$500K/year is sufficient to justify a microfocus based CT system for dedicated use. The justification includes the capability of the system to provide radioscopic visualization of component internal details as a very useful complement to CT. Such a system acquisition can be planned to support the high resolution materials development CT activity as well as the electronics parts activity. Use of CT for larger electromechanical and mechanical systems does not appear to offer enough incentive to justify acquisition of a CT system capable of scanning the larger parts, solely for failure analysis, at the activity level of even a larger manufacturer. The needs for larger parts analysis can often be met by a service facility or a facility purchased predominantly for other evaluation requirements. However, it was clear from this work that a service facility would only be an effective option if the service were readily available and accessible without substantial paperwork or delay. A facility that can handle large structures and provide the desired sensitivity to detail for the electromechanical systems would be of value to major manufacturers, although the economic justification will most likely need to be based on a major large structure evaluation requirement.

Presently CT is relatively new and, therefore, its capacity to provide cost-effective and often unique information is not fully appreciated. In order to make CT truly valuable, analysts must become familiar with results and data manipulation possibilities as well as testing techniques. For example, simultaneous scanning of good and defective parts is often very useful for identifying anomalies. The fact that, within limitations of the facility, CT can be applied to intact systems

under operational stress and environmental conditions (pressure, temperature, mechanical actuation, etc.) adds a powerful capability to the failure analysis laboratory and may permit failure mode identification under service conditions that are impossible to study with traditional methods.

CT has also been shown to be a useful tool for composite material evaluations. Analysis of both anomalous material (errors in fabrication or design and damage) and good materials (process evaluation) is of interest. Although occasional requirements occur for macrographic information from CT on larger composites, very high resolution imaging is most often required because features of interest tend to be on the scale of individual laminations (better than 0.05 mm). Unfortunately, this limits the size of the component that may be examined. Examples of both extremes are represented by the spoiler and the stress damaged composite test coupon discussed in this report. With the spoiler, the part size required a large scale industrial scanner, but the water invasion pathways are expected to be on the scale of the ply thicknesses. Therefore, direct detection of the anomalies was unlikely, and the CT analysis could only be expected to be an adjunct to other examination methods. Where composites can be examined micrographically, CT can be very beneficial and less costly than layer-by-layer dissection. Techniques such as mathematical morphology greatly extend the power of CT over other methods and offer insights into material behavior that can probably not be derived by other approaches.

4.3 System Justification

Personnel responsible for failure analysis are generally easily persuaded of the benefits of CT when exposed to the sorts of example cases that have been evaluated in this program. In many instances it has been possible to estimate the cost savings associated with CT examination of specific parts and materials, but as should be clear from much of this discussion, a large share of the benefits of CT are intangible (although very real) and it is difficult to associate a cost saving justification with them. Unfortunately, management asked to invest in CT capability most often requires a specific bottom-line cost justification before approval. Unquantifiable benefits such as risk reduction or customer satisfaction do not compute at the accounting department.

In large companies requiring substantial failure analysis and quality assurance activities, it becomes unnecessary to base equipment justification on specific tests. A statistical pattern can be identified that can be used to develop average cost saving estimates for the laboratory activities. An example is provided by the justification developed recently to support a request to purchase an approximately $400K CT facility for an electronics part failure analysis laboratory as shown in Figure 4.3-1. The laboratory conducts about 18,000 man-hours of parts evaluations per year. When the work load was examined in light of the lessons learned in this program, it was apparent that approximately one-third of the work could have been done effectively with CT. The estimated time savings would have been 60% averaged over all applicable cases. Therefore, the same evaluations could have been conducted with 14,400 man-hours (12,000 hours not affected by CT + 0.4 x 6000 hours to which CT was applicable). At this stage, no account was taken of the fact that the quality of evaluations would have been improved as a result of the relatively unambiguous view of the parts afforded by CT. The net hours savings would be 3600 hours which, at nominally $100/hour, would result in a yearly saving of $360K. CT system utilization was estimated at 50% on a 1000 hour/year availability basis. Therefore, additional cost savings could be expected from the CT system as its availability and capabilities became commonly known for other users.

Discussions have been presented in earlier reports [1,6,12] that can complete the overall economic picture and develop a pay-back schedule, but this level of analysis is typically not required for capital investment decisions in the present case. The capital request process at most companies is designed to take intangibles into account. The cost justification, which in this case is very substantial, is presented along with a subjective evaluation of the "impact on company business" of a negative decision. In this case, improved accuracy of failure investigations, reduced schedule

time, ability to analyze cases that could not be completed with other techniques, the intangible value of correctly understanding failure modes critical to the integrity of company products and, customer satisfaction were all cited. Ultimately, the CT asset would reduce liability costs for warranty and flightline rework by improving the development and qualification process. The intangibles, in this instance, were strong since safety issues could be identified, but overall, the investment was approved because a good balance of costs and business benefits could be established. A supportable statistical analysis of affected work load was presented that indicated very meaningful savings relative to system cost, and understandable intangible benefits could be cited.

Electronic Parts Failure Analysis Laboratory Workload:

18,000 Hours/year @ ~ \$100/ Hr ⟶ \$1.8M/year

Application of High Resolution CT with Radioscopic Capability:

- Estimated @ 33% of Workload
- On-Site System Will Reduce Effort 60% for Applicable Parts

↓

Net Workload:

12,000 + 0.4(18,000/3) = 14,400 Hours

↓

Savings:

(18,000 - 14,400) x \$100/Hr ⟶ $\boxed{\text{\$360K/Year}}$

Note: At present, not all submitted components can be analyzed owing to inadequate diagnostic capability. CT will also increase success rate.

Figure 4.3-1 Economic justification of CT/radioscopic system for electronics parts failure analysis.

5.0 CONCLUSIONS

The CTAD program has evaluated the use of CT for a variety of failure analysis investigations. CT has been shown to aid analyses by eliminating disassembly and/or destructive sectioning or, at the least, by providing a useful procedural guide while the more traditional methods are carried out. CT is often a more rapid means of failure investigation because it provides easily understood internal views of assemblies without requiring any time consuming and destructive invasive procedures. In fact, it is not uncommon to perform CT on systems without removing them from storage or shipping containers. Because the process is completely nondestructive, the parts being examined retain their integrity for further examination and test or for reuse if warranted by conclusions of the investigation. These benefits were summarized in Table 4.1-1. It was also apparent that the concept of failure analysis must be broadly interpreted since many applications of CT involve examination of developmental hardware and materials to determine whether they are performing up to design specifications. In other cases, CT provides assurance that a part that is performing off-optimum is not doing so because of a failure, but only because some element of the assembly was at or near a tolerance limit. In such cases, CT permits part acceptance with the assurance that acceptable performance will continue.

For the most part, relatively high resolution requirements were identified with typical parts entering the failure analysis and materials development laboratories although significant exceptions were encountered. Figure 5.0-1 summarizes these points.

CT for Failure Analysis

- Electronics failure analysis laboratories can benefit from CT capability
  - Combination radioscopic (RTR)/micro-CT may be best approach
  - Electronic components need 0.1 mm or better resolution
- CT enables more reliable failure analysis of electromechanical assemblies than traditional methods
  - Electromechanical assemblies need 0.25 mm resolution at 400 kV or above
  - Fast response, ready access to CT capability is needed
- Composite failure can be analyzed with CT
  - CT systems with better than 0.05 mm resolution are necessary
  - 3-D imaging significantly enhances analysis; mathematical morphology is a convenient, intuitive approach

Figure 5.0-1 Conclusions with respect to CT systems requirements and applications for failure analysis.

A general purpose CT system for failure analysis would need the high resolution available in small volume industrial systems, the capability to handle large objects with high energy X-rays for penetration, and have fast scanning. These are conflicting criteria for the construction of any one CT system. Thus, the availability of a variety of systems is desirable. The use of multiple slice CT for three-dimensional modeling is very useful in failure analysis evaluations. Scanning speed is a critical parameter for any CT system data acquisition especially when many slices are required.

With the frequent requirements, in failure analysis, for many slices, development of "cone beam" or volume viewing CT systems that have adequate inherent resolution and contrast sensitivity can be expected to make an important advance in providing economic implementation of CT imaging.

Combining radioscopy (real-time radiography (RTR)) with CT, as is possible with high resolution microfocus CT systems, adds considerable power to failure investigations. The ability to view the part radioscopically while it is manipulated and operated can be of considerable help in focusing in on potential failure modes of miniature and, frequently, complex devices. CT then offers needed refinement of the examination to finalize the investigation. The two methods are excellent complements to one-another. For electronic failure analysis laboratories of sufficient size, a small microfocus based CT system would be a worthwhile acquisition. The system could provide multipurpose high resolution radioscopic or digital radiographic examinations as well as fCT. Such a system would be in the range of expense of scanning electron microscopes, which are common tools of these laboratories. A purchase can be justified strictly from economic considerations if the workload is sufficiently high.

Simultaneous scanning of failed and known-good parts was also identified as a powerful strategy for isolating defects where failure causes can be very subtle. The excellent dimensional fidelity of CT images can be used to advantage in these cases to make careful comparisons between critical dimensions of the good and failed parts.

Studies of damage in composite materials emphasized the value of the detailed digital, volumetric density map that the CT system can produce. Having the data in digital form opened the possibility for mathematical processing of the image to levels of high sophistication. The use of mathematical morphology to extract and isolate details of defect structures in composites is a good example of the power available for CT data processing. The result of the data processing was an intuitive, and easily understood picture of the internal condition of the damaged composite that could not have been generated, realistically, in any other way.

A CT system need not necessarily be purchased in every case, but should be available to every failure analysis laboratory. A CT service capability, set up to readily assist failure analysis organizations with scanning and interpretation, could be worthwhile if a sufficient number of failure analysis laboratories participated. However, during the analyses conducted for this program, participating failure analysts repeatedly pointed out that they would only consider CT if it could be accessed routinely, with little lost time, and without undue paper work. Thus, a successful service facility will have to provide for nearly "on-line" service under an open contract with the user. In very large organizations, the failure analysis needs extend across many groups and they all must to be aware of the availability and applicability of CT to assist them in performing their functions better.

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